

GHRs Observations of the Lyman α Forest

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Abstract.

I review the results obtained using the GHRs on low redshift Lyman α absorbers. Until the advent of HST and the GHRs, the existence of such absorbers was doubted. The confirmation of their existence, in one of the first GHRs GTO team results to be published, must rank as one of the HSTs most interesting results. The GHRs resolution allows us to probe equivalent widths well below those detectable with the FOS, and has led to a number of interesting new questions. One example is the apparent disagreement between the GHRs result that there are many Lyman α absorbers which are **not** associated with luminous galaxies, and FOS studies which suggest that **all** such absorbers have a nearby galaxy causing them. This almost certainly shows that the equivalent width (or column density) range reachable by the GHRs includes gas from a wide range of causes, and not only the halos of luminous galaxies. With these data, we are seeing the debris left over from Galaxy formation, material flung out from galaxy interactions and starbursts, and also diffuse halo material at the outer edges of normal galaxies.

1. The picture prior to HST

The Lyman α ‘forest’ refers to the dense overlapping absorption seen shortward of the Lyman α emission line in high redshift QSO spectra (see figure 1 for an example, taken from Lu et al. 1996). This absorption is caused by a huge number of foreground condensations of warm gas, with a significant component of neutral hydrogen. Nice reviews of the observational situation just prior to the launch of HST are given by Carswell 1988, and Hunstead 1988. A non-specialist summary would be: the detectable neutral hydrogen column densities in the forest vary from less than 10^{13} cm^{-2} up to $\sim 10^{17} \text{ cm}^{-2}$, above which the systems become optically thick to the Lyman continuum (referred to as Lyman-limit systems), and generally show Mg II absorption. There is a roughly power law fall-off in density of absorbers with column density, such that it is considered reasonable to associate these rarer Lyman-limit systems with the inner regions of the halos of luminous (L^*) galaxies. Above $10^{15.5} \text{ cm}^{-2}$, C IV absorption is often detected, and so these systems are called ‘metal-line’ systems, although recent Keck HIRES observations suggest that the carbon abundances are comparable in the lower column density systems as well (around 0.01 solar, Cowie et al. 1995).

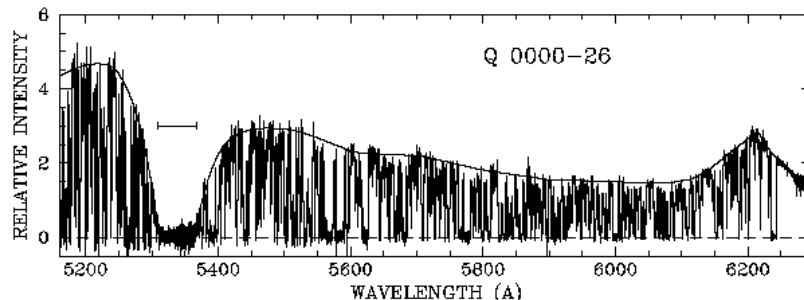


Figure 1. The high redshift Lyman α forest, taken from Lu et al. 1996. This is a Keck HIRES spectrum of Q0000-26, in arbitrary flux units, with resolution $\sim 6.6 \text{ km s}^{-1}$. Only the Lyman α forest portion is shown in order to illustrate the adopted continuum level (smooth solid curve). Note the damped Lyman α absorption at $z_{abs}=3.39$ or $\lambda=5337\text{\AA}$.

and Songaila and Cowie 1996). The absorbers have line widths corresponding to temperatures in the range $10^4\text{--}5 \text{ K}$, consistent with their being photo-ionised by the UV background, and do not show strong clustering. All the above led to a model in which the absorption was produced by inter-galactic clouds, probably made up of pristine material left over from (or not yet part of) the process of galaxy formation. It has also been noted (see for example Rauch and Haehnelt 1995) that estimates of the ionisation fraction in these clouds, along with big-bang limits for the baryon density of the universe, suggest that, at high redshift, these low column density absorbers may contain a substantial fraction of **all** the baryons in the universe. The Lyman α forest at high redshift is not an exotic trace component.

The biggest problem in understanding the forest prior to launch of the Hubble Space Telescope (HST) was that Lyman α absorption could only be seen from the ground when it had been redshifted beyond 3200\AA , i.e. a redshift of 1.6. As can be seen from figure 2, this only covers ages from around 1 to 3 Gyrs, leaving the period from 3 Gyrs to the present (8-12 Gyrs) unobservable. It also meant that redshift surveys for galaxies at the same redshifts as the absorbers were impossible, and so tests of the association between absorbers and galaxies could not be made.

However, over the redshift range from $z=4$ to $z=1.6$, a steep fall-off in absorber density per unit redshift was seen (see Lu, Wolfe and Turnshek 1991 for example). Fitting a power law to this fall-off, and extrapolating to the present day, one would predict that there should be essentially no detectable Lyman α absorbers left, making the advantages of UV studies of the forest moot.

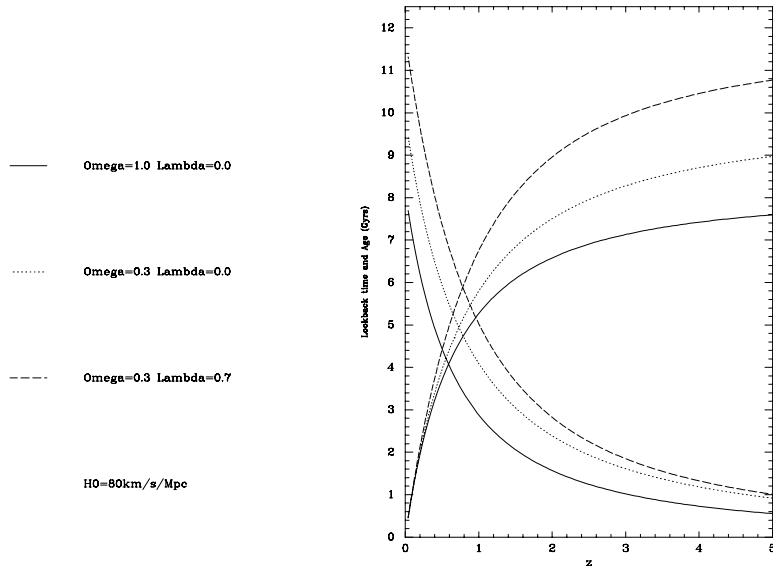


Figure 2. Lookback time and age of the Universe in units of 10^9 years for 3 different cosmologies. The main point is to note that the redshift range of Lyman α absorbers visible from the ground ($1.6 < z < 5$) only covers ages from around 1 to 3 Gyrs.

2. HST/GHRS observations of 3C273.0 and line densities

After the launch of HST, one of the Goddard High Resolution Spectrograph (GHRS) team's highest priority projects was to observe the brightest QSO in the sky – 3C273.0. This QSO, with a redshift of 0.158, has an optical magnitude of 12.8, and IUE observations had confirmed its strong UV flux, making it the best extragalactic target for absorption line studies.

GHRS observations a low resolution with the G140L grating, and medium resolution with the G160M grating were obtained, and were described in Morris et al. 1991. Low resolution FOS observations were published at the same time by Bahcall et al. 1991. Figure 3a is the GHRS G140L spectrum, with resolution of $\sim 2,000$, showing the entire wavelength range over which Lyman α absorption can be seen. Marked around 1250\AA is the region observed with the G160M grating shown in Figure 3b. This spectrum has resolution $\sim 15,000$, and shows a large number of strong galactic absorption lines (discussed in detail in Savage et al. 1993). Features which can not be ascribed to ions in our galaxy are assumed to be Lyman α absorption from clouds along the line-of-sight (LOS) to 3C273.0. Marked around 1253\AA is one of the regions observed with the Ech-A grating. Figure 3c shows this (as yet unpublished) GHRS Ech-A spectrum, which was obtained much later, with resolution $\sim 100,000$. In it, the strong Lyman α line

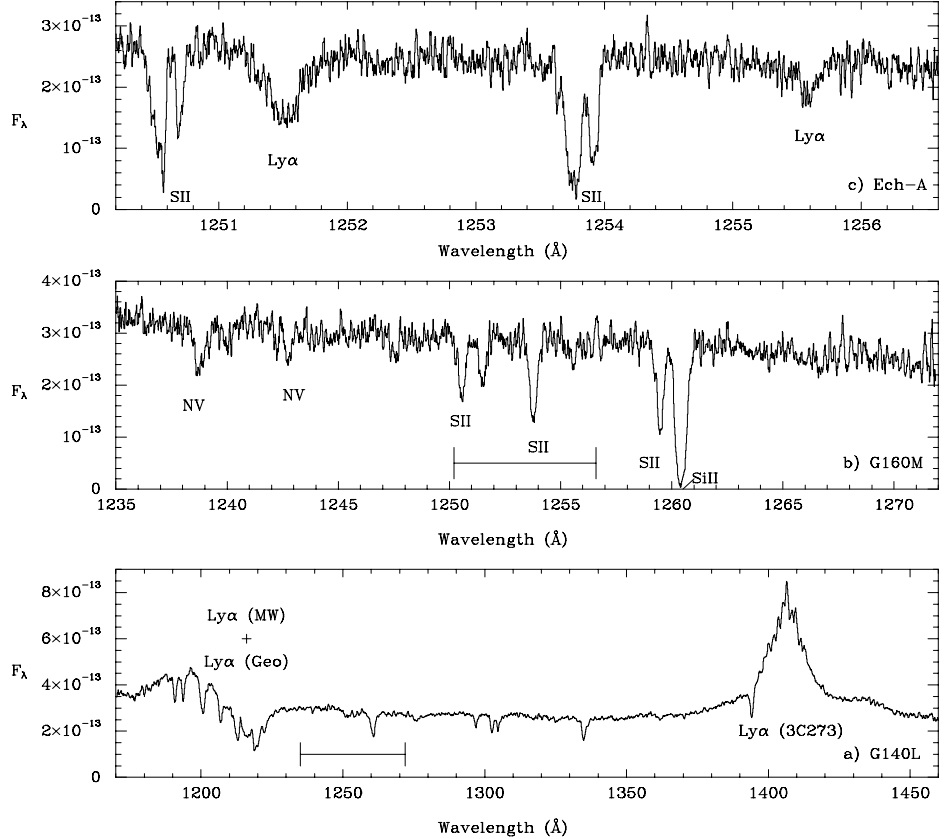


Figure 3. GHR Spectra of the QSO 3C273.0. (a) GHR G140L spectrum with resolution of $\sim 2,000$, (b) GHR G160M spectrum with resolution $\sim 15,000$, (c) GHR Ech-A spectrum with resolution $\sim 100,000$. All the spectra have been smoothed with a boxcar of width 4 pixels, matching the spectral resolution.

near 1251.5\AA can be seen to be clearly resolved. With a resolution of $\sim 3 \text{ km s}^{-1}$, this is one of the highest dispersion observations of an extra-galactic Lyman α absorption at **any** redshift. The original GHR data set was published in Brandt et al. 1993, while an additional G160M spectrum of the interesting low redshift region covering the Virgo cluster velocity range was published by Weymann et al. 1995. The three panels of Figure 3 show how valuable high spectral resolution is in detecting and studying weak absorption lines, such as those of the Lyman α forest.

The studies above showed that Lyman α absorption was indeed still present at the present day, and hence that some flattening of the fall-off in line density with time must occur. Since then, the HST Absorption Line Key Project, carried out with the FOS, has observed many more LOS, albeit at low resolution, and has begun to quantify the change in slope of the number density with redshift for the stronger lines (see Bahcall et al. 1993, Bahcall et al. 1996, with a dissenting

view presented by Bechtold 1994). Thus, although the luxuriant Lyman α forest at high redshift has been dramatically thinned out, there remains a Lyman α savannah at the present day, suitable for study.

3. Correlations between absorbers and galaxies

At last Lyman α absorbers, with column densities in the same range as those making up the forest at high redshift, were available at distances within which galaxies could be studied. So, are the absorbers always associated with a luminous galaxy, or are they inter-galactic clouds randomly distributed in space? In the 3C273.0 LOS, as many as 17 absorbers were identified. Morris et al. 1993 published a galaxy redshift survey complete to an optical magnitude of ~ 19 , and out to a radius of 1° from the QSO LOS. Figure 4 shows the locations of absorbers and galaxies from that survey. Angles have been exaggerated by a factor

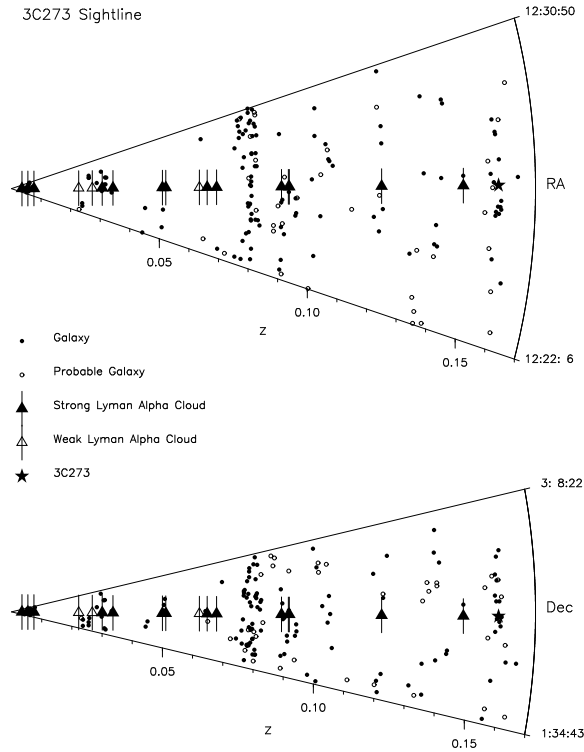


Figure 4. Pie-diagrams for the galaxies and absorbers observed in the 3C273.0 LOS from Morris et al. 1993.

15 to prevent overcrowding of the symbols, which results in a highly distorted

plot. Initially spherical structures (such as the 3C273.0 cluster of galaxies) appear elongated transverse to the line of sight. Morris et al. 1993 also published deep optical imaging around the QSO, searching for faint dwarf galaxies near the LOS, which was followed up by Rauch, Weymann and Morris 1995. Neither of these studies found any suitable candidates. Morris et al. 1993 showed narrow band imaging, searching for Balmer line ($H\alpha$) emission at the same velocity as a couple of the lowest redshift absorbers. No such emission was found. This line emission was looked for with higher sensitivity by Williams and Schommer 1993, who claimed a detection, but this was shown not to be real by Bland-Hawthorn et al. 1994. Finally, Morris et al. 1993 and Van Gorkom et al. 1993 searched for 21 cm radio emission, without success.

After this intensive search of the 3c273.0 LOS, there remained clear cases of absorbers with no galaxy of any sort within a radius of 4-5 Mpc. On the other hand, statistical analysis of the correlation between the absorbers and galaxies by Morris et al. 1993, and examined in more detail by Mo and Morris 1994, showed that the absorbers definitely were not distributed at random with respect to the galaxies. These results are summarised schematically in Figure 5. Three

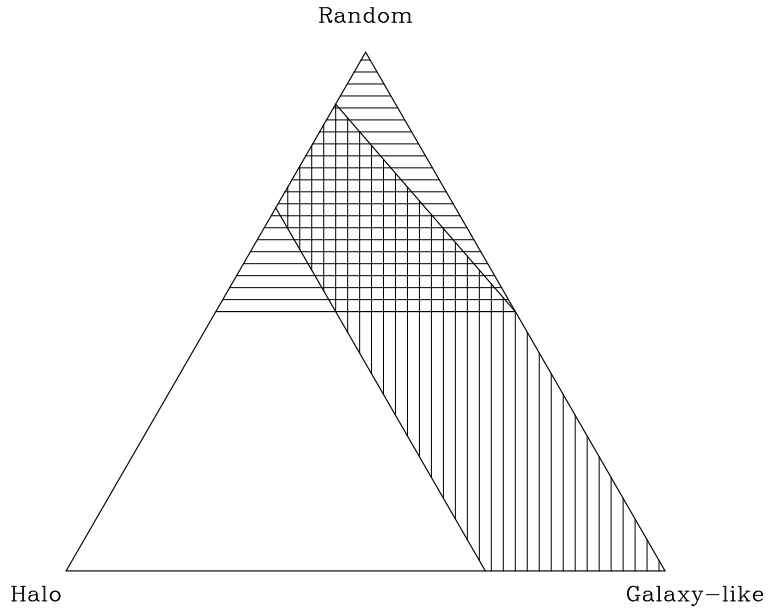


Figure 5. Schematic diagram showing the permitted combinations of the 3 Lyman α model populations from Mo and Morris 1994. Vertical shading is the region permitted by the 0.5 Mpc scale correlations, while horizontal shading shows the region permitted by the 10 Mpc scale correlations.

Lyman α model populations were considered by Mo and Morris 1994: randomly distributed, distributed like galaxies, but not actually part of an observed galax-

ies halo, or in fact part of an observed galaxy's halo. The vertices of the triangle represent models with a single type of absorber (random, galaxy-like or halo). Moving along the sides of the triangle represents different admixtures of two different types of absorber, while the inner regions represent mixtures of all three types of model. Marked along the edges are the permitted ranges found by the Monte-Carlo tests of Mo and Morris 1994. For simplicity, they just drew straight lines between these bounds to roughly illustrate the areas with three absorber populations which are permitted. It can be seen that there is a substantial region permitted by both the 10 (large scale) and 0.5 Mpc (small scale) correlation strength (the region where the vertical and horizontal hatching overlaps). The majority of the absorbers have to be uncorrelated with galaxies in order to produce the weak large scale correlation. The observed small-scale correlation with galaxies can be produced by a relatively small admixture of halo absorbers (as little as 10%), although the data is also consistent with galaxy halos producing up to 30% of the observed absorption lines. If none of the absorption is produced by such halos, i.e. if there are no absorbers physically associated with a galaxy in the sample with measured redshifts, then the observed correlations are marginally consistent with a 50:50 mix of random and galaxy-like absorbers.

Morris and van den Bergh 1994 took these results, and showed that a mixture with a dominant population of randomly distributed absorbers, along with an admixture of material tidally stripped from galaxies, both matched the observations, and made physical sense. The 21 cm image of the streamers of HI in the M81 group published by Yun, Ho and Lo 1994 gives a visually compelling illustration of the effects of tidal interactions on gas in galaxies. In the meantime, Smooth Particle Hydrodynamic (SPH) and other numerical modelling of the growth of structure of the universe was approaching the present epoch (e.g. Hernquist et al. 1996, Katz et al. 1996). These simulations showed that low column density absorption could be widely distributed, and can be caused by: "filaments of warm gas, caustics in frequency space produced by converging velocity flows, high density halos of hot collisionally ionised gas, layers of cool gas sandwiched between shocks, and modest local undulations in undistinguished regions of the intergalactic medium" (Katz et al. 1996). I.e., the prediction from SPH modelling was that the Lyman α forest was, like most forests, a very complex eco-system.

4. Column density dependence of absorber properties

It therefore came as something of a surprise when Lanzetta et al. 1995, and their accompanying press release, announced that "... (the) mysterious clouds of hydrogen in space may actually be vast halos of gas surrounding galaxies. This conclusion runs contrary to the longstanding belief that these clouds occur in intergalactic space" (HST Press release # STScI-PR95-22). Their survey of 46 galaxies near the LOS to 6 QSOs observed with the FOS as part of the HST Absorption line Key Project showed that at least $32 \pm 10\%$ and possibly as high as $60 \pm 19\%$ of the absorbers detected in those LOS were part of the halos of L^* galaxies. A couple of lines of observational evidence supported this conclusion. First, as shown in their figure 23, (although one might quibble about the sample definition and effects of upper limits) there is a correlation between absorber

Equivalent Width (EW) and impact parameter to the nearest galaxy. Secondly, independent work by Dinshaw et al. 1995 was showing that absorber ‘sizes’, determined from observations of close pairs of QSOs with the FOS, were very large – several hundred kpc. Also there was some theoretical support for this idea, as discussed for example in Maloney 1992, Salpeter 1993, and Salpeter and Hoffman 1995. An nice independent commentary on this issue is given by Carswell 1995.

How can these two results be reconciled? It should first be admitted that the uncertainties in both papers (Morris et al. 1993 and Lanzetta et al. 1995) are large enough that they could well be consistent with each other. However, it seems more likely to me that, as suggested by the SPH results of Hernquist et al. 1996, the correlation between absorbers and galaxies has a fairly strong dependence on column density. The correlation claimed by Lanzetta et al. 1995 is based on lines with EW greater than 0.3\AA , while the sample studied by Morris et al. 1993 was dominated by lines with EW $\sim 0.03\text{--}0.1\text{\AA}$. For typical line widths, this maps on to column densities greater than 10^{14} cm^{-2} for Lanzetta et al. 1995, and from $1\text{--}3\times 10^{13}\text{ cm}^{-2}$ for Morris et al. 1993.

Stocke et al. 1995, Le Brun et al. 1996, and Bowen, Blades and Pettini 1996 investigate the correlation between EW and impact parameter in their figures 4, 4 and 3 respectively. Stocke et al. 1995 used the GHRS to observe a well chosen sample of Seyfert galaxies known to lie on the far side of voids in the galaxy distribution. Their main conclusion is that some absorbers are indeed found within the voids, although there was evidence that the absorber density is lower in voids than elsewhere. They also show that the claimed correlation between absorber EW and impact parameter breaks down for EW less than 0.3\AA . Le Brun et al. 1996 and Bowen, Blades and Pettini 1996 use LOS observed with the FOS to cast doubt on even the large EW end of the correlation. As is commonly claimed in such situations “more observations are needed”. It would be very interesting if a large transition in correlation properties could be shown to occur between the ‘GHRS’ and ‘FOS’ column density ranges.

5. Work in progress

In this review, for pedagogical reasons, I have neglected to mention the issue of cloud-cloud correlations, and chosen to focus on cloud-galaxy correlations instead. The former area is nevertheless one of great interest for people studying clouds at both high and low redshift. In a poster at this conference, some recent GHRS results are presented by Tripp, Lu and Savage 1996, suggesting there is significant clustering of weak Lyman α absorbers around strong ones at low redshift.

I would like to conclude this review with one piece of work in progress which might help clarify the strong EW situation. One problem with most QSO LOS is that one has no idea of the shape of the absorber projected on the sky, let alone in three dimensions. In figure 6, I show results from redshift surveys around the QSO pair Q0107-025A,B. The low- z absorbers were found in GHRS observations were taken with the G140L grating. Because of the comparative faintness of the QSOs, higher dispersion observations were not possible. This figure includes 32 galaxy redshifts from CFHT and also redshifts from the Palomar 5m. Of par-

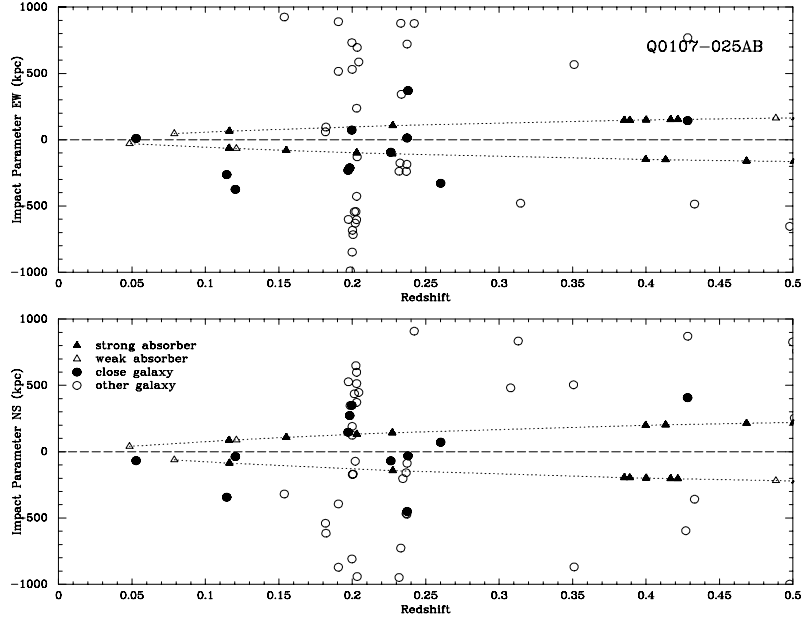


Figure 6. Pie-diagrams for the galaxies and absorbers in the LOS to the QSO pair Q0107-025A,B.

ticular interest are the Lyman α absorbers seen in both lines of sight. One near $z \sim 0.23$ seems to be associated with a bright early type galaxy near both lines of sight. In contrast, any galaxy associated with the absorption near $z \sim 0.4$, which includes a Lyman limit system in the ‘B’ line of sight, remains undiscovered. With this data, we can now at least begin to map out the projected shapes of absorbers.

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